United States Department of Agriculture

Natural Resources Conservation Service

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Subject: ENG -- Electromagnetic Induction (EMI) Assistance **Date:** 18 September 2000

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Purpose:
Electromagnetic induction (EMI) methods were used to help locate and map the extent of seepage along an embankment of a farm pond near Toms Brook in Shenandoah County, Virginia.

Participants:
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Mike Liskey, Natural Resource Conservationist, USDA-NRCS, Stephens City, VA

Activities:
All field activities were completed on 11 September 2000.

Equipment:
The electromagnetic induction instrument used in this study was the GEM300 sensor. The GEM300 sensor is manufactured by Geophysical Survey Systems, Inc. ♦ Won and others (1996) have described the use and operation for this sensor. The GEM300 sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed intercoil spacing of 1.3 m. The sensor records both in-phase and quadrature measurements. Output is the mutual coupling ratio in parts per million or apparent conductivity (mS/m).

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,♦ was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search.

Field Procedures:
An EMI survey was completed along the portion of the embankment where seepage was suspected to occur. Five survey lines were established parallel with the centerline of the embankment. Survey lines were spaced at intervals of 10 feet and spanned both sides and the crest of the embankment. Survey markers were inserted in the ground at intervals of 25 feet along each survey line. This procedure provided 45 reference points.

Surveys were conducted with the GEM300 sensor operated in the continuous mode and in both the horizontal and vertical dipole orientations. The location of each observation point recorded with the GEM300 sensor was processed and adjusted by the MAGMAP96 software program.♦ The GEM300 sensor was configured to record an observation every 2 seconds. This procedure resulted in 211 observation points. In-phase, quadrature phase, and conductivity data were recorded at four different frequencies (5010, 9810, 14790, and 19050 Hz) at each observation point. Frequencies of 9810 and 14790 Hz correspond to the operating frequencies of the EM31 and EM38 meters (manufactured by Geonics, Limited♦), respectively.

EMI:
Background:

♦ Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA- NRCS

Electromagnetic induction is a noninvasive geophysical tool that has been used to investigate of dam foundations (Butler et al., 1989) and to locate water-bearing fracture zones in bedrock (McNeill, 1991; Olayinka, 1990). Advantages of EMI are its portability, speed of operation, flexible observation depths, and moderate resolution of subsurface features. Results of EMI surveys are interpretable in the field. This geophysical method can provide in a relatively short time the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions, planning further investigations, and locating sampling or monitoring sites.

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the volumetric water content, type and concentration of ions in solution, amount and type of clays in the soil matrix, and temperature and phase of the soil water (McNeill, 1980). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976). Because of their higher moisture contents, it was expected that areas of seepage would have slightly higher conductivity than adjoining areas of the embankment and, if sufficiently contrasting, could be detected with EMI.

Electromagnetic induction measures vertical and lateral variations in apparent electrical conductivity. Values of apparent conductivity are seldom diagnostic in themselves, but lateral and vertical variations in these measurements can be used to infer changes in earthen materials. Interpretations are based on the identification of spatial patterns within data sets. To assist interpretations, computer simulations are normally used

Depth of Observation:

With the GEM300 sensor, the depth of penetration or the "skin depth" is estimated using the following formula (McNeill, 1996):

$$D = 500/(s*f)^{-2} \qquad [1]$$

Where s is the ground conductivity (mS/m) and f is the frequency (kHz). With the GEM300 sensor held at hip height in the vertical dipole orientation, the average apparent conductivities were 29.9, 27.9, 40.5, and 45.3 mS/m at frequencies of 5010, 9810, 14790, and 19050 Hz, respectively. Based on equation [1], the selected frequencies and these averaged conductivities, the estimated skin depths were about 41 m at 5010 Hz, 30 m at 9810 Hz, 20 m at 14790 Hz, and 17 m at 19050 Hz. Within the defined skin depth, earthen materials from all depths contribute, in varying degrees, to the measured response. With increasing depth, the relative contribution from various depth layers passes through a maximum. While the induced magnetic fields may achieve these estimated skin depths, the strengths of the response diminish with increasing depth and are too weak to be sensed by the GEM300 sensor.

The depth of observation is often defined as the depth that contributes the most to the total EMI response measured on the ground surface. Although contributions to the measured response come from all depths, the contribution from the *depth of observation* is the largest (Roy and Apparao, 1971). As noted by Roy and Apparao (1971), for any system, the depth of observation is a good deal shallower than is generally assumed or reported. As no depth-weighting functions are presently available for the GEM300 sensor, it is unclear what depth is providing the maximum response. However, it is clear that the depth of observation is a good deal shallower than the skin depth.

In many EMI studies, negative conductivity values are removed by electronic nulling of the data set. The negative offset was not taken out of the GEM300 data. As a consequence, negative apparent conductivity values appear in the data and simulated plots. Negative values are often associated with "metallic" cultural features such as the buried corrugated metal principal spillway.

Results:

No conspicuous indications of seepage were discerned along the portion of the embankment surveyed. Figure 1 includes plots of in-phase data collected with the GEM300 sensor in the vertical dipole orientation and at frequencies of 5010, 9810, 14790, and 19050 Hz. The frequency at which data were collected is shown above each plot. In-phase data are more sensitive to metallic objects than data collected in the quadrature phase and is often referred to as the "metal detection" phase. Plots appearing in Figure 1 help to confirm the location of the buried principal spillway and the extent of the area in which electromagnetic fields are influenced by this feature. Each plot shows data collected at different frequencies and provides a slightly different picture of the embankment. Presumably, low frequency data shows conditions and features at deeper skin depths than high frequency data. In each plot, the isoline interval is 25 ppm (parts per million). In each plot, a dark line has been drawn that approximates the location of the buried corrugated metal principal spillway. This feature interferes with the electromagnetic fields and produces conspicuous anomalies in the data. When the electromagnetic field of the sensor intercepts an electrically conductive object (buried metallic features), current flows through the object, producing anomalous values. Depending on whether the object is ferrous or nonferrous, the anomalous values may manifest themselves as opposite polarities at different frequencies.

Apparent conductivity data collected with the GEM300 sensor in the horizontal and vertical dipole orientations are shown in figures 2 and 3, respectively. Data collected in the horizontal dipole orientation (Figure 2) represents shallower depths than data recorded in the vertical dipole orientation (Figure 3). In each plot the isoline interval is 2 mS/m. The frequency at which data were collected is shown above each plot. The depth of observation is presumed to increase as the frequency decreases.

In general, for each frequency, apparent conductivity increases towards the lower-lying areas of the embankment. This trend is presumed to principally reflect changes in moisture content; higher lying areas have lower moisture contents and are more removed from the water table. A majority of the spatial patterns apparent in Figure 2 parallel the long axis of the embankment with few, relatively inconspicuous trends that are orthogonal to the long axis of the structure. These spatial patterns do not suggest seepage. However, in each plot of Figure 3, the right-hand portion of the embankment contains bands of higher conductivity that traverse the structure near the principal spillway. These bands may represent areas of possible seepage, higher clay content, and/or areas of electromagnetic field interference caused by the principal spillway. The area between reference points 25 and 75 feet on the x axis (see Figure 3) is considered worthy of further study.

Table 1 summarizes the apparent conductivity data collected with the GEM300 sensor. With the exception of data collected at 9810 Hz, average and medium values of apparent conductivity increase with increasing observation depths (lower frequency). For each frequency, the average, minimum, and maximum apparent conductivity values were affected by the presences of the principal spillway and other sources of "cultural noise."

Table 1

Basic Statistics for theGEM300
Apparent Conductivity
(All values are in mS/m)

Horizontal Dipole Orientation

	5010	9810	14790	19050
AVG.	29.4	27.4	38.9	42.7
MIN.	-92.0	8.6	24.8	27.1
MAX.	76.3	54.3	77.1	74.9
FIRST	26.6	24.0	35.6	39.3
SECOND	28.8	26.7	39.0	42.3
THIRD	31.7	29.4	41.1	45.6

Vertical Dipole Orientation

	5010	9810	14790	19050
AVG.	29.9	27.9	40.5	45.3
MIN.	7.7	-18.8	15.4	26.1
MAX.	62.0	53.7	63.4	114.1
FIRST	23.8	22.7	35.5	40.7
SECOND	28.8	27.5	39.8	44.3
THIRD	33.1	32.1	45.2	49.8

Conclusions:

1. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations are interpretive and do not substitute for direct ground-truth observations (soil borings or well logs). The use of geophysical methods can reduce the number of coring observations, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.

2. The location of the principal spillway was readily apparent in the in-phase data collected at four frequencies. Patterns of apparent conductivity appear to principally parallel the long axis of the embankment and are presumed to reflect differences in moisture contents. However, the right-hand portion of the embankment appears to contains bands of higher conductivity that traverse the structure near the principal spillway. These bands may represent areas of possible seepage, higher clay content, and/or areas of electromagnetic field interference caused by the principal spillway.

3. In order to assess the significance of the anomalies and spatial patterns disclosed by EMI, engineers and geologist familiar with the embankment should review the accompanying plots. The EMI data can also be correlated with the other available data, to better understand possible seepage pathways.

It was my pleasure to work in Virginia and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

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EMI SURVEY
EMBANKMENT OF FARM POND
TOMS BROOK, VIRGINIA
INPHASE DATA
VERTICAL DIPOLE ORIENTATION

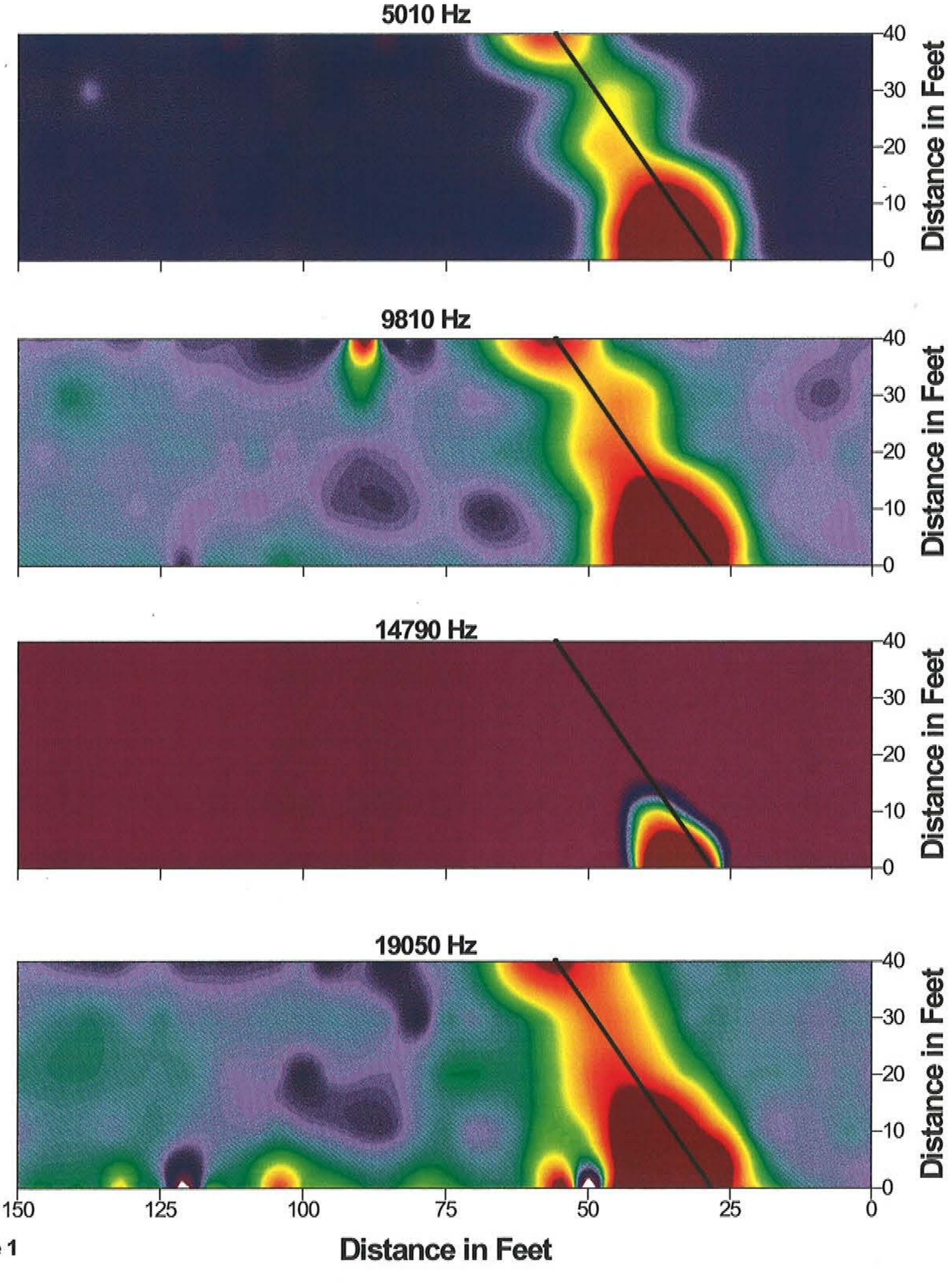

Figure 1

EMI SURVEY
EMBANKMENT OF FARM POND
TOMS BROOK, VIRGINIA
HORIZONTAL DIPOLE ORIENTATION

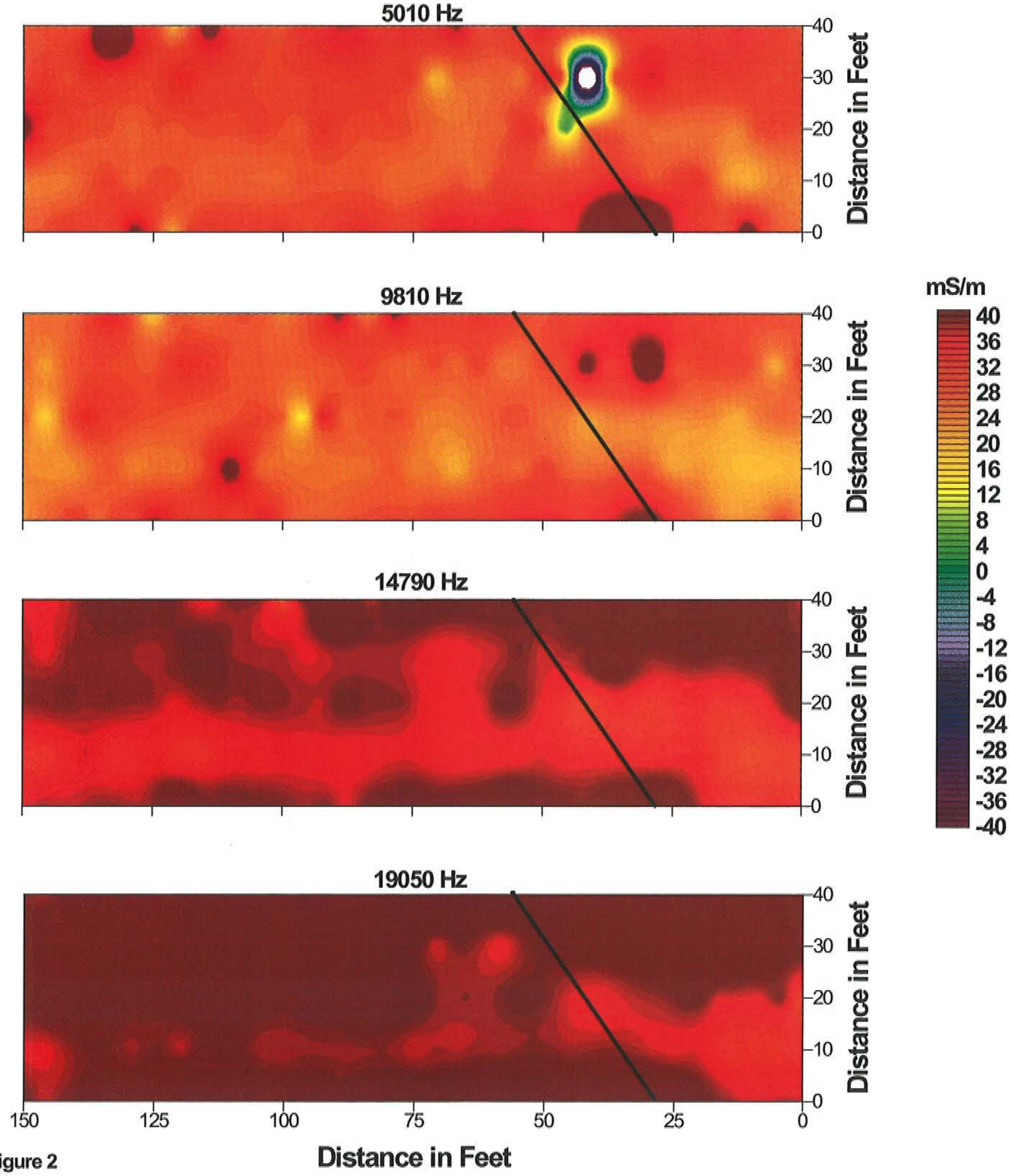

Figure 2

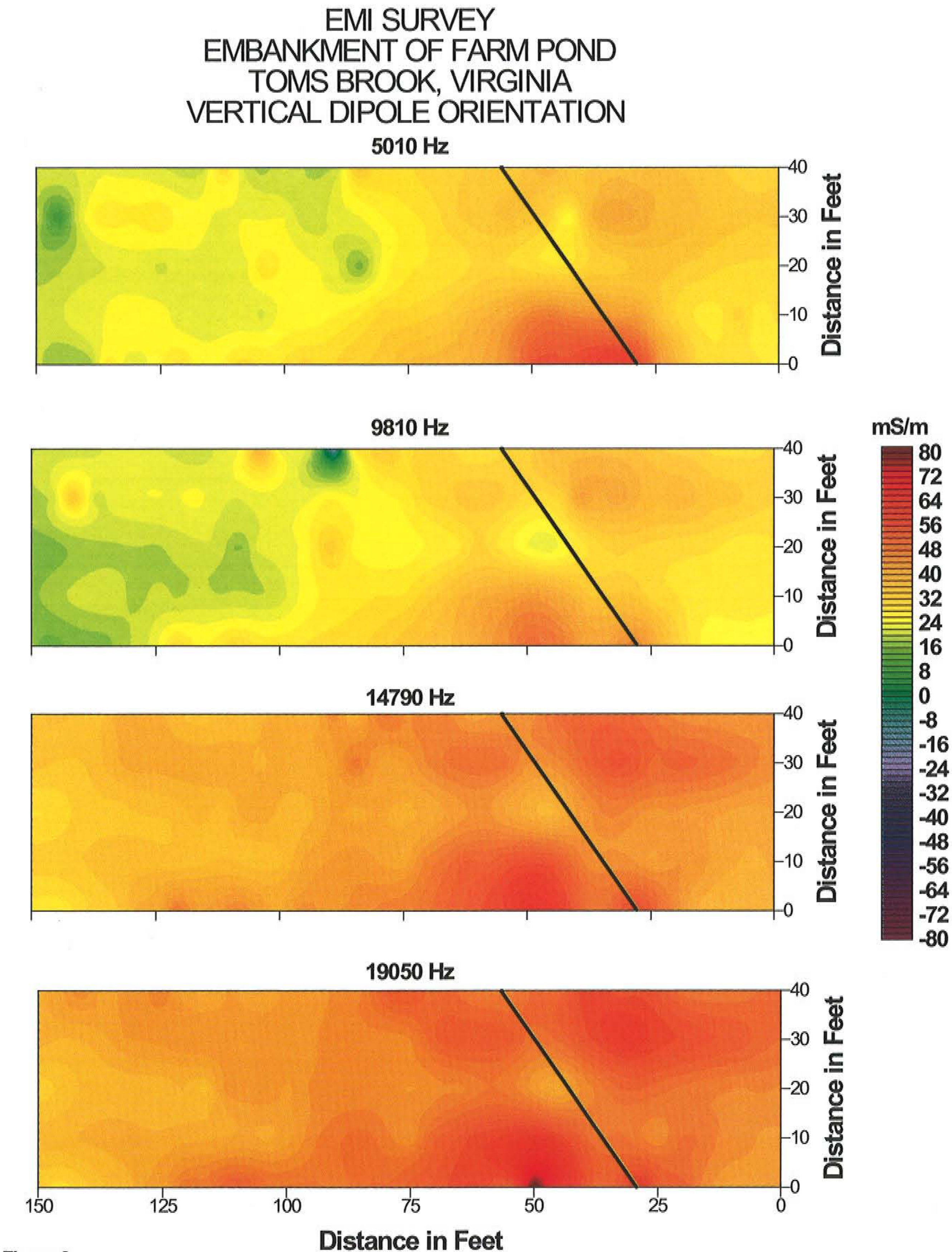
EMI SURVEY
EMBANKMENT OF FARM POND
TOMS BROOK, VIRGINIA
VERTICAL DIPOLE ORIENTATION
5010 Hz
9810 Hz
14790 Hz
19050 Hz
Distance in Feet
mS/m
80
72
64
56
48
40
32
24
16
8
0
-8
-16
-24
-32
-40
-48
-56
-64
-72
-80
150
125
100
75
50
25
0
40
30
20
10
0

Figure 3